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Changes in attention to an emotional task after sleep deprivation: Neurophysiological and behavioral findings

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ABSTRACT

While sleep loss is shown to have widespread effects on cognitive processes, little is known about the impact of sleep loss on emotion processes. In order to expand on previous behavioral and physiological findings on how sleep loss influences emotion processing, we administered positive, negative, and neutral affective visual stimuli to individuals after one night of sleep deprivation while simultaneously acquiring EEG event related potential (ERP) data and recording affective behavioral responses. We compared these responses to a baseline testing session. We specifically looked at the late positive potential (LPP) component of the visual ERP as an established sensitive measure of attention to emotionally-charged visual stimuli. Our results show that after sleep deprivation, the LPP no longer discriminates between emotional and non-emotional pictures; after sleep deprivation the LPP amplitude was of similar amplitude for neutral, positive, and negative pictures. This effect was driven by an increase in the LPP to neutral pictures. Our behavioral measures show that, relative to baseline testing, emotional pictures are rated as less emotional following sleep deprivation with a concomitant reduction in emotional picture-induced anxiety. We did not observe any change in cortisol concentrations after sleep deprivation before or after emotional picture exposure, suggesting that the observed changes in emotion processing are independent of potential stress effects of sleep deprivation. Combined, our findings suggest that sleep loss interferes with proper allocation of attention resources during an emotional task.

1. Introduction

Sleep loss has been shown to impact various aspects of cognitive processes (Killgore, 2010; Lim & Dinges, 2008; McCoy & Strecker, 2011). However, compared to the clear impairments in attention that have been shown after sleep loss, sleep loss has been found to have mixed results on emotion processing. In particular, some studies have shown decreased emotionality after sleep loss indicated by blunted affect (Talbot, McGlinchey, Kaplan, Dahl, & Harvey, 2010), impaired accurate recognition of human emotions (Van der Helm, Gujar, & Walker, 2010), decreased emotional expressiveness (Minkel, Htaik, Banks, & Dinges, 2011), and reduced emotional intelligence (Killgore et al., 2008). However, other studies have found increased emotionality after sleep loss indicated by exaggerated responses to negative stimuli (Tempesta et al., 2010), increased amygdala activity in response to emotionally negative stimuli (Yoo, Gujar, Hu, Jolesz, & Walker, 2007), and increased reward network activity in response to emotionally positive stimuli (Gujar, Yoo, Hu, & Walker, 2011). These differences may be due to dissimilar testing methodologies between studies (e.g. different types of self-report assessments of sleepiness and emotion, hemodynamic brain responses). An alternative explanation here is that the changes in emotion that occur after sleep loss are due to impairments in attention (Chuah et al., 2010; Sterpenich et al., 2009; Yoo et al., 2007). In other words, changes in tonic alertness due to sleep loss can impact emotion processing because emotional stimuli lose their ability to capture attention resources. Thus, in spite of an increase in amygdala activation after sleep deprivation, a decrease in attention to emotional stimuli would still result in a decrease in emotion processing and reactivity. In support of this theory, the increased amygdala activity seen after sleep loss is also associated with a decrease in amygdala-PFC functional connectivity, suggesting a reduction in emotion control processes after sleep deprivation (Yoo et al., 2007).

In order to expand on previous behavioral and physiological findings on the effect of sleep loss on emotion processing, we used behavioral measures (keyboard number pad ratings) combined with electroencephalographic (EEG) event related potentials (ERPs)

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in response to non-emotional compared to emotional pictures after one night of sleep deprivation. We used positive and negative emotional pictures since these two picture categories have different effects on attention. Negative stimuli elicit more attention than positive stimuli and studies which have used ERPs to understand emotion processing show that negative pictures are more effective than positive pictures at capturing attention resources (Öhman & Mineka, 2001; Olofsson, Nordin, Sequeira, & Polich, 2008; Schupp, Öhman, et al., 2004).

ERPs were used since they can complement existing fMRI work due to their precise temporal resolution of the onset and duration of emotional processes and their great promise in explaining patterns of cortical reactions to emotional visual stimuli (Olofsson et al., 2008). The late positive potential (LPP) component of the visual ERP is specifically established as a sensitive measure of attention to emotionally charged visual stimuli (Cuthbert, Schupp, Bradley, Birbaumer, & Lang, 2000; Keil et al., 2002; Olofsson & Polich, 2007). Induction of the LPP is thought to serve as a neurobiological correlate of motivated attention to stimuli of adaptive significance (sex, death, etc.). In other words, because these stimuli are inherently arousing, they require the preferential allocation of limited attention resources (Lang, Simons, & Balaban, 1997). In support of this idea, evidence suggests that the LPP is involved in memory formation for emotional events (Dolcos & Cabeza, 2002; Palomba, Angrilli, & Mini, 1997). Emotional modulation of the LPP is highly stable – it has been shown to be consistent over time within individuals and is not sensitive to habituation (Codispoti, Ferrari, & Bradley, 2006; Hajcak, MacNamara, & Olvet, 2010).

The aim of the current study was to investigate the influence of 24 h of sleep deprivation on emotion processing. To that end, we measured behavioral and ERP LPP measures of emotion processing during a baseline morning testing session and compared those responses to a morning testing session following 24 h of sleep deprivation. The current study directly tested the idea that sleep deprivation interferes with the allocation of attentional resources to an emotional task. The emotional task measures included the LPP ERP amplitude with concomitant behavioral ratings to emotionally positive, negative, and neutral pictures. In order to complement our emotion measures, we also assessed anxiety during baseline and sleep deprivation sessions both before and after emotional picture exposure since sleep fragmentation has been shown to have anxiolytic effects in rats (Tartar et al., 2009). Finally, we measured salivary cortisol levels in order to examine the extent to which any observed changes in emotion processing could be related to sleep deprivation-induced changes in morning cortisol levels. Since we observed robust changes in the LPP after sleep deprivation, we followed up these findings with a control ERP experiment to ensure that any deviations from baseline were a result of sleep deprivation as opposed to habituation to the emotion task.

2. Methods

2.1. Participants

Participants were recruited via flyers posted around campus or through a university research participation website. A total of twenty-two healthy right-handed participants with normal or corrected-to-normal vision were recruited for this study. Twelve participants were tested in the first experiment which directly assessed the effects of sleep deprivation relative to a baseline testing condition. This experiment consisted of a baseline testing session and one night of sleep deprivation two days later followed by a second ERP testing session. They also underwent sleep monitoring as well as anxiety and stress assessment. One participant was removed after the baseline testing session because the baseline testing session showed no difference in the LPP between emotional and non-emotional picture categories. One additional participant did not return after baseline testing, leaving ten participants in the sleep deprivation experiment (5 males, mean age = 23, SD = 3.97, range 19–30). Ten participants underwent only the ERP testing portion of the experiment with no sleep deprivation (4 males, mean age = 21, SD = 2.80, range = 18–27) in two sessions scheduled two days apart. These participants were tested as a follow-up experiment to explicitly ensure that the LPP results observed in the sleep deprivation group were not due to habituation effects. Since this group did not undergo sleep deprivation, there was no reason to monitor their sleep or test them for sleep deprivation-induced changes in morning cortisol or anxiety. Every participant was first administered the Epworth Sleepiness Scale (ESS) in order to pre-screen for potential sleep disorders or conditions associated with excessive daytime sleepiness (enrollment criterion was a score of less than 10). No participants were excluded based on ESS score criterion. In addition, all study participants were asked to refrain from caffeine use 24 h prior to, and during, study participation. The recruitment and testing procedures were approved by and carried out according to a protocol submitted to the Nova Southeastern University (NSU) Institutional Review Board. Participants in the sleep deprivation experiment were compensated for their time with a $100 gift card to a local store and participants in the control experiment were compensated for their time with either a $10 gift card to a local store or research participation credit as part of an Introduction to Psychology course requirement.

2.2. Stimuli and design

Visual ERPs were elicited from participants while they viewed pictures selected from the International Affective Picture System (IAPS) (Lang, Bradley, & Cuthbert, 1997). Picture presentation and timing were controlled through the use of Presentation software (Neurobehavioral Systems, LLC). There were 105 trials and each trial began with a 400 ms randomized presentation of either a negative ($n = 35$), neutral ($n = 35$) or positive ($n = 35$) independent IAPS pictures. The 400 ms picture on-time was chosen since even briefly presented pictures capture attention resources, but also has the advantage of better evoking both early posterior negativity (EPN) and LPP components (Schupp, Junghöfer, Weike, & Hamm, 2004). A central fixation point was present in the center of the screen throughout the experiment. Following the picture presentation, a black screen was on for the rest of the trial (4000 ms) during which time the participants were instructed to categorize the picture, via a keyboard button press, before the next trial began. All pictures were presented on a 23-in. LCD monitor with a vertical refresh rate of 60 Hz.

Independent picture sets were used for the first and the second testing session and the order was counter-balanced across participants. The IAPS normative ratings (Lang et al., 1999) were used to select the neutral, negative, and positive pictures. The average valence for each picture category (neutral, negative, and positive) was matched in the two picture sets. The average picture valences were as follows: neutral pictures set 1 mean = 5.11, SD = 0.32, neutral pictures set 2 mean = 5.09, SD = 0.26, negative pictures set 1 mean = 2.35, SD = 0.51, negative pictures set 2 mean = 2.35, SD = 0.62, positive pictures set 1 mean = 7.51, SD = 0.47, positive pictures set 2 mean = 7.47, SD = 0.46.[1] Image sets were also matched for arousal ratings within valence category. Negative and positive images were significantly more arousing than neutral images. However, the negative images were also significantly more arousing than the positive images. The average picture arousal levels were as follows: neutral pictures set 1 mean = 3.60, SD = 0.72, neutral pictures set 2 mean = 3.35, SD = 0.84, negative pictures set 1 mean = 5.89, SD = 0.81, negative pictures set 2 mean = 5.93, SD = 0.70, positive pictures set 1 mean = 4.95, SD = 0.76, positive pictures set 2 mean = 5.01, SD = 0.93. Accordingly, the central selection criterion here was along the dimension of picture valence and our operational definition of "emotional" refers strictly to the pleasantness or unpleasantness of the pictures.

2.3. Procedure

All EEG testing occurred between 7:00 and 9:00 a.m. and included one baseline testing session and one sleep deprivation or ERP/picture control testing session two days later. All participants first filled out a brief demographics form during the first testing session. The participants were seated in a dimly lit sound-attenuated room. Participants were then fitted with an electrode cap and EOG electrodes. The

[1] IAPS picture directory reference numbers for the images used in the present study. Neutral picture set 1: 6910, 7002, 7009, 7014, 7019, 7030, 7033, 7036, 7040, 7044, 7052, 7056, 7057, 7061, 7080, 7096, 7130, 7161, 7180, 7184, 7188, 7205, 7207, 7224, 7237, 7247, 7249, 7287, 7354, 7487, 7546, 7500, 7560, 8060, and 8312. Neutral picture set 2: 7000, 7003, 7010, 7017, 7020, 7025, 7031, 7034, 7037, 7041, 7045, 7053, 7058, 7062, 7081, 7100, 7140, 7160, 7170, 7182, 7185, 7187, 7190, 7211, 7235, 7242, 7255, 7290, 7365, 7493, 7506, 7547, 7820, 8065, and 8232. Negative picture set 1: 1052, 1201, 1271, 2053, 2205, 2276, 2375.1, 2683, 2799, 2800, 3000, 3001, 3005.1, 3010, 3017, 3030, 3060, 3064, 3230, 3400, 6021, 6212, 6260, 6312, 6510, 6530, 6831, 9181, 9290, 9491, 9520, 9561, 9902, 9903, and 9927. Negative picture set 2: 1051, 1202, 1274, 2095, 2455, 2688, 2730, 2811, 2900, 3015, 3016, 3053, 3062, 3063, 3261, 3266, 3301, 3350, 3500, 3530, 6022, 6213, 6250, 6311, 6415, 6550, 6834, 9075, 9184, 9291, 9530, 9600, 9901, 9904, and 9922. Positive picture set 1: 1440, 1463, 1500, 1721, 1750, 1999, 2045, 2058, 2080, 2154, 2170, 2260, 2314, 2341, 2360, 2398, 2540, 4007, 4533, 4597, 4610, 4643, 4676, 5621, 5825, 5831, 5982, 7330, 7350, 7492, 7580, 8170, 8420, 8499, and 8540. Positive picture set 2: 1441, 1610, 1620, 1811, 2035, 2050, 2070, 2091, 2160, 2209, 2224, 2274, 2332, 2345, 2395, 2550, 2650, 4090, 4535, 4599, 4614, 4650, 4668, 5480, 5594, 5700, 5829, 5833, 7200, 7400, 7502, 8185, 8470, 8501, and 8510.

task required the participants to view randomly presented emotional (positive and negative) and neutral pictures. Participants were told to rate each picture with a keyboard button press, with hands rested on the keyboard and prepared to press, on a scale of 1–9 (unpleasant–pleasant) as soon as the picture turned off and that they would have 4 s to rate each picture. They were told to try to refrain from blinking until one second after the picture turned on. Participants were first given a brief practice session with viewing and rating non-experiment pictures to ensure that they understood the instructions. During EEG data acquisition all participants were closely visually monitored and were given corrective instructions if they were blinking or moving too much. For example, if a participant blinked during a picture they were told, "Try to only blink about a second after the picture turns off."

2.4. Additional procedure for sleep deprivation participants

The participants were issued an activity monitor and a sleep diary (along with instructions on how to use both) two days prior to baseline testing. Actiwatch actigraph wrist monitors (AWScore, Mini Mitter Co., Inc., Sun River, OR, USA) and sleep diaries were used to confirm total sleep time and to ascertain that participants were not sleep deprived the night preceding baseline testing. The participants were issued an activity monitor and a sleep diary (along with instructions on how to use both) two days prior to baseline testing. Total sleep time data were derived from the Actiwatch monitors utilizing the default software provided with the monitors. Sleep diaries were used to corroborate bed times and wake times utilized in the calculation of total sleep time via Actiwatch software.

Participants in the sleep deprivation experiment first reviewed their sleep diaries and actiwatch recording with the experimenter to ensure that all of the information was correct. Following this, they filled out the Spielberger State-Trait Anxiety Inventory (STAI) prior to and after picture exposure (Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983). Saliva was also collected from each participant by unstimulated passive drool before and after picture exposure for salivary cortisol analysis. Immediately after collection, the sample tubes were stored in a −20 °C freezer. Cortisol was quantified via human enzyme immunoassay (EIA) kits (Salimetrics LLC, USA). Women's hormonal contraceptive use and menstrual phase were assessed during both sessions using self-report. Since the control group did not undergo sleep deprivation, sleep monitoring, anxiety and cortisol measures were not taken in this group.

During the sleep deprivation evening the participants came to the laboratory at 7:00 p.m. for overnight total sleep deprivation with only themselves and 1–2 researchers present. The participants were required to wear their activity monitors throughout this period and they were constantly monitored. In order to help keep them awake, the participants were allowed to engage in passive activities (e.g. talking to the experimenter, board games, etc.). No food or beverages other than water were permitted during the overnight sleep deprivation period.

2.5. Electrophysiological recordings and data analyses

EEG assessment was conducted using Contact Precision Instruments' Psychlab EEG amplifying and recording equipment (Contact Precision Instruments, Cambridge, MA). Electrodes were attached using an EEG cap (Electrocap International) at Fz, Cz, Pz, C3, C4, O1, and O2 electrode location with a cap (Electro-Cap International, Eaton, OH) fitted with recessed, pure tin electrodes placed in accordance with the International 10–20 System. Eye movements and eye blinks were monitored via tin electrodes (Electro-Cap International, Eaton, OH) placed above and at the outer canthus of the left eye. Signals were referenced to linked electrodes attached to earlobes. Electrode impedance was maintained at less than 5 kΩ. Procedures for infection control specified by the Society for Psychophysiological Research were followed in attaching and removing electrodes (Putnam, Johnson, & Roth, 1992). The EEG amplifier was set at a gain of 30,000 and the sampling rate of the EEG was 500 Hz. High pass filters were set to .1 Hz and low pass filters were set to 40 Hz. A 60 Hz notch filter was active. The data were analyzed offline through the use of Psylab8 software (Contact Precision Instruments, Cambridge, MA). For the ERP analyses, 1000 ms of raw EEG data were epoched to the respective stimulus presentation including 100 ms of pre-stimulus baseline. The LPP was measured as the average voltage 300–800 ms following picture onset. Trials in which the EOG exceeded ±75 μV were excluded from the final averaged ERP. The ERP trials were also visually examined and individually rejected at each electrode location for any additional observed artifact (e.g. blocking, movement, alpha). For the sleep deprivation experimental group, an average of 8 out of 105 trials were excluded due to artifacts during the baseline morning (range = 7–10) and an average of 10 trials were excluded the morning after sleep deprivation (range = 7–33). For the ERP control experimental group, an average of 9 trials were excluded due to artifacts during first morning (range = 5–12) and an average of 8 trials were excluded during the second morning (range = 4–14).

2.6. Statistical analyses

Repeated Measures (RM) Analysis of Variance (ANOVA) was used to examine the effect of picture category and session on the visual LPP amplitude, picture ratings, and rating response latencies in the sleep deprivation and picture control groups. Group status (sleep deprivation, control) served as a between-subjects factor while session (day 1, day 3), and picture category (positive, negative, neutral) served as within-subject factors. Based on planned comparisons, significant interaction effects were followed up by within group comparisons using RM ANOVA where picture category (positive, negative, neutral) and session (day 1, day 3) served as the within-subject factors. In addition, a RM ANOVA was carried out to test for changes in anxiety and cortisol in the sleep deprivation group with session (baseline, sleep deprivation) and collection time (before pictures, after pictures) as the within-subjects factors. Post hoc pairwise comparisons were carried out using a Bonferroni correction for multiple comparisons and paired samples t tests. In instances where the sphericity assumption was not met, the reported p-values associated with the F statistics were adjusted via the Greenhouse–Geisser correction. All calculations were conducted using an SPSS statistical package (version 19, SPSS inc., IBM). All reported p values are two-tailed with an a priori significance level of $p < 0.05$.

3. Results

3.1. Actigraphy

A combination of observation and actigraphy confirmed sleep deprivation during the overnight sleep deprivation protocol. The night before baseline testing, actigraphic sleep analyses showed that participants slept an average of 309 min (SD = 60.15), sleep diaries used to corroborate sleep time and wake time yielded similar results (mean total sleep time 306 min, SD = 75.50).

3.2. LPP amplitude

Due to an early finding of electrode location effects, combined with previous findings that the LPP is most robust at centro-parietal sites and that an occipital early negativity is also prevalent in ERPs to emotional pictures, we analyzed the average of electrode locations Cz and Pz (Cuthbert et al., 2000; Foti, Hajcak, & Dien, 2009; Schupp et al., 2000, and see Schupp, Flaisch, Stockburger, & Junghöfer, 2006, for review). The RM ANOVA comparing the sleep deprivation and control experimental groups showed no significant group main effects. There was a significant main effect for picture ($F(2,36) = 32.84$, $p < 0.001$). Bonferroni correction showed that the average LPP was significantly larger for the negative ($M = 3.76$, SE = 0.53) and positive pictures ($M = 4.20$, SE = 0.59) compared to neutral pictures ($M = -0.37$, SE = 0.46), all p's < 0.001. There was also a significant picture × group interaction ($F(2,36) = 4.50$, $p = 0.02$) and a significant three way picture × session × group interaction ($F(2,36) = 3.43$, $p = 0.04$). These interactions were decomposed by RM ANOVAs for each group.

Fig. 1 presents the grand average LPPs to the three picture categories (neutral, positive and negative) separated by testing session for the sleep deprivation group. The 2 (session) × 3 (picture category) RM ANOVA of the sleep deprivation group showed a significant main effect for picture ($F(2,18) = 10.73$, $p < 0.001$). Bonferroni corrections for the main effect of picture revealed that, overall, LPP amplitude was significantly larger on positive (mean = 3.54, SE = 0.82) and negative (mean = 3.22, SE = 0.65) picture trials compared to neutral (mean = 0.64, SE = 0.54) picture trials. In support of the idea that sleep deprivation alters emotion processing, there was a significant session × picture interaction ($F(2,18) = 4.55$, $p = 0.03$). While not significant, the LPP amplitudes to the emotional picture categories decreased after sleep deprivation compared to baseline testing. The LPP to the neutral pictures increased after sleep deprivation compared to baseline testing. Post hoc t-test analyses showed that the LPP amplitude to the neutral pictures was significantly larger after sleep deprivation (mean = 2.22, SD = 2.40) compared to the baseline condition (mean = −0.34, SD = 2.20; $t(9) = -2.49$, $p = 0.04$).

Fig. 2 shows the grand LPPs to the three different picture categories for the control LPP experiment wherein participants were exclusively exposed to the pictures in two different testing sessions (without sleep deprivation before the second testing session). These results support the hypothesis that the LPP amplitude and

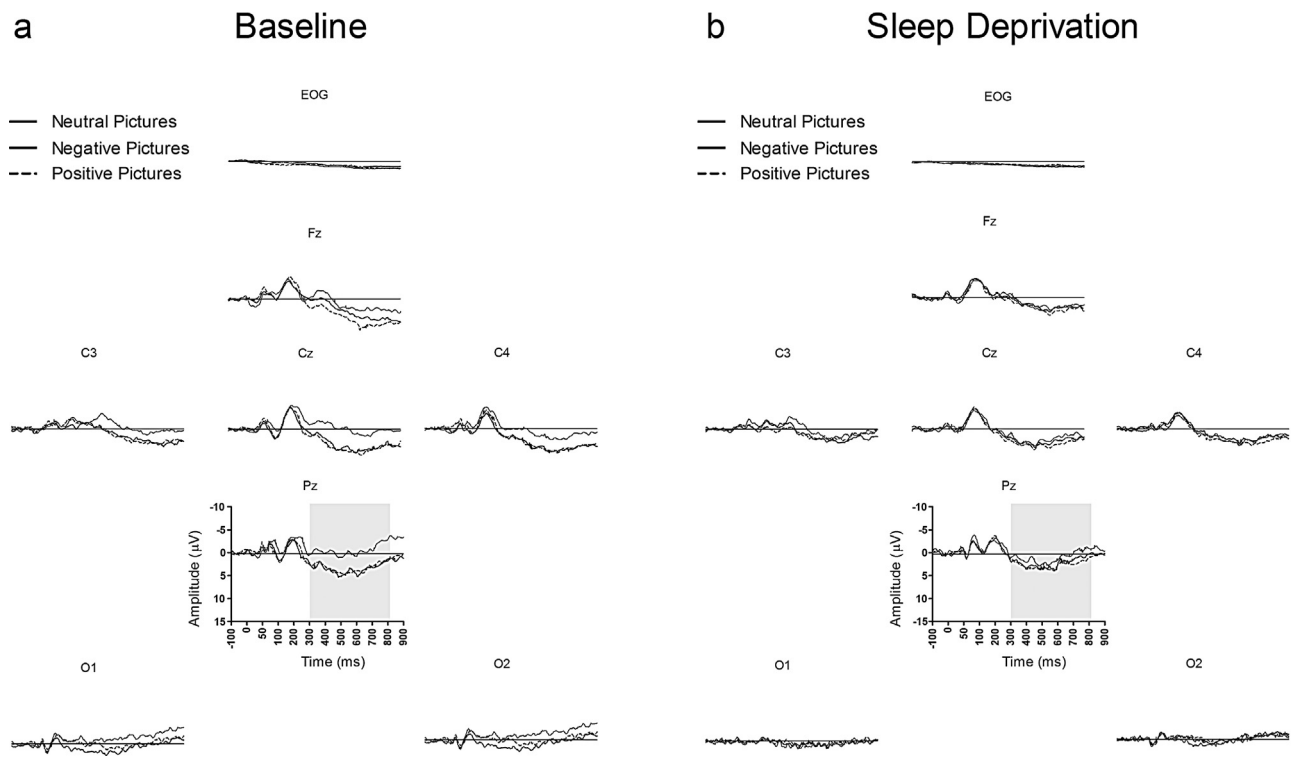

Fig. 1. Visual LPP ERPs for baseline (a, left) compared to sleep deprivation (b, right) conditions. Participants were exposed to an emotionally negative, positive, or neutral picture for 400 ms. Light gray box on Pz graph depicts the analyzed latency range for the LPP. *Y* axis represents voltage (μV) and *x* axis represents time (ms).

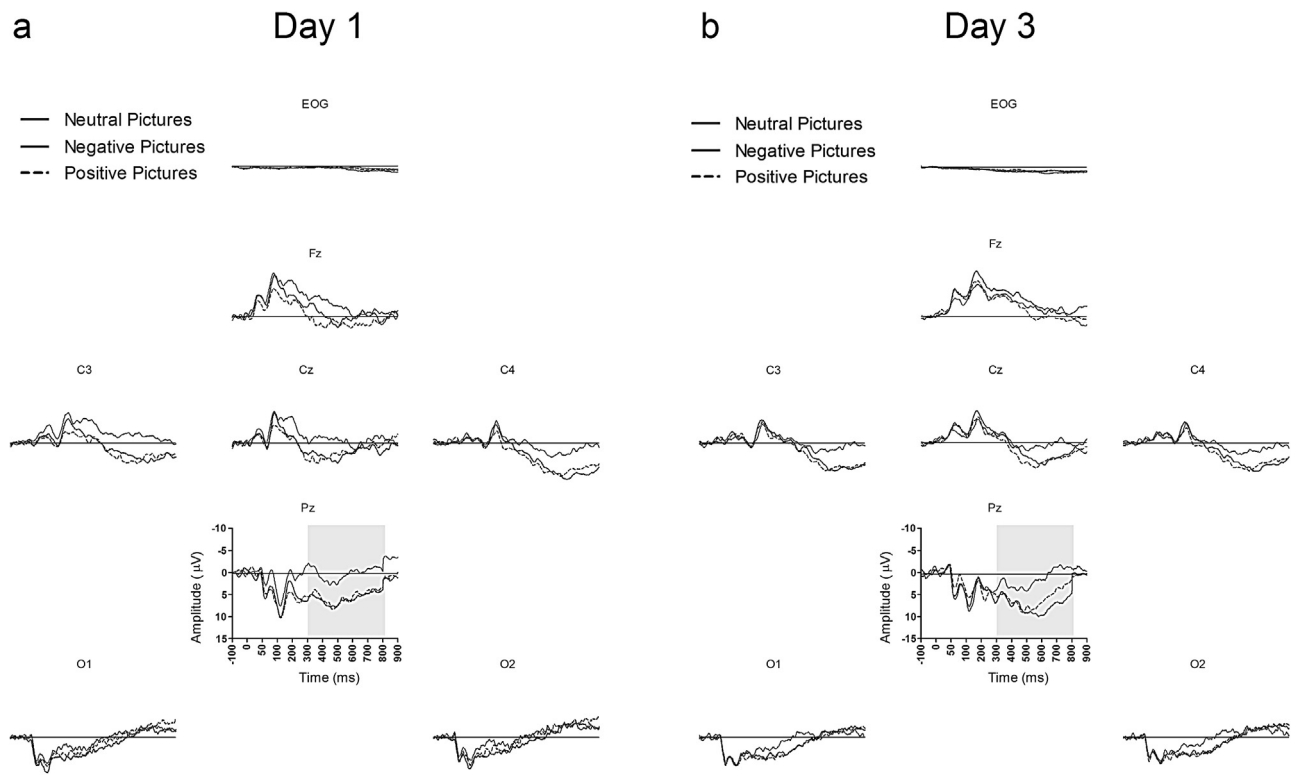

Fig. 2. Visual LPP ERPs for the control ERP condition in which participants were tested on a baseline day (a, left) and again two days later (b, right). As with the experimental portion of the study, participants were exposed to an emotionally negative, positive, or neutral picture for 400 ms. Light gray box on Pz graph depicts the analyzed latency range for the LPP. *Y* axis represents voltage (μV) and *x* axis represents time (ms).

Table 1
Means and standard deviations of picture valence ratings and response latencies.

		Baseline or control test day 1				Sleep deprivation or control test day 3	
		M	SD			*M*	SD
	Picture			ERP control group	Picture		
Valence ratings	Neutral	5.35	0.34		Neutral	5.09	0.33
	Positive	7.09	0.59		Positive	6.79	1.06
	Negative	2.32_a	0.85		Negative	2.89_b	1.30
Response latencies (ms)	Neutral	950	323.92		Neutral	986	336.52
	Positive	958	333.60		Positive	994	365.58
	Negative	989	329.39		Negative	1020	307.12
	Picture			Sleep deprivation group	Picture		
Valence ratings	Neutral	5.12	0.74		Neutral	5.06	0.33
	Positive	6.40	1.46		Positive	6.05	1.22
	Negative	3.04	0.92		Negative	3.67	1.18
Response latencies (ms)	Neutral	967	303.14		Neutral	1125	426.22
	Positive	1055	410.90		Positive	992	440.83
	Negative	1030	435.78		Negative	1061	516.85

Note: Means between columns with differing subscripts are significantly different at $p < 0.05$ based on paired samples *t*-tests.

picture ratings are not sensitive to a repeated testing session. The 2 (session) × 3 (picture category) RM ANOVA of the control group showed a significant main effect for picture ($F(2,18) = 20.87$, $p = 0.001$). There was not a main effect for session, ($F(2,18) = 0.07$, $p = 0.80$) nor a session × picture interaction ($F(2,18) = 0.74$, $p = 0.49$). Post hoc pairwise comparisons revealed that, as expected, the LPP amplitude was significantly larger on positive (mean = 5.18, SE = 1.35) and negative (mean = 5.17, SE = 1.39) picture trials compared to neutral (mean = 0.31, SE = 1.03) picture trials.

3.3. Valence ratings

Table 1 shows behavioral ratings and response latencies for the picture responses. The RM ANOVA comparing the sleep deprivation and control experimental groups on response latencies showed no significant group main effects or any interaction effects. The RM ANOVA comparing the sleep deprivation and control experimental groups on picture valence ratings (1–9, negative–positive) showed no significant group main effects. However, there was a significant picture rating × group interaction ($F(2,36) = 3.29$, $p = 0.04$) as well as a significant picture rating × session interaction ($F(2,36) = 5.71$, $p = 0.007$). These interactions were decomposed by RM ANOVAs within each group.

Follow up RM ANOVA in the sleep deprivation group showed a significant main effect for picture ($F(2,18) = 19.50$, $p < 0.001$) as well as a significant session × picture interaction ($F(2,18) = 3.9$, $p = 0.04$). Post hoc tests revealed that negative pictures were rated as significantly less negative after sleep deprivation (mean = 3.66, SD = 1.18) compared to the baseline session (mean = 3.04, SD = 0.92; $t(9) = -2.38$, $p = 0.04$). As expected, in the control group there was a significant effect of picture rating ($F(2,18) = 80.80$, $p < 0.001$). The ratings for all three picture categories were consistent with IAPS normative data (Lang et al., 1999), confirming that the control participants were paying attention to the task. We did not find a significant main effect for session ($F(1,9) = 0.001$, $p = 0.97$) or a significant session × picture interaction ($F(2,18) = 2.28$, $p = 0.13$). The lack of an interaction confirms that, consistent with the LPP ERP findings, the picture ratings are not sensitive to a repeated testing session.

3.4. Cortisol and anxiety

Cortisol and anxiety data are presented in Table 2. RM ANOVA for the cortisol measure did not show a main effect for session ($F(1,9) = 0.49$, $p = 0.50$), a main effect for collection time ($F(1,9) = 2.16$, $p = 0.18$), or a session × collection time interaction effect ($F(1,9) = 0.31$, $p = 0.59$). RM ANOVA for the state anxiety measure did not show a main effect for session ($F(1,9) = 0.63$, $p = 0.45$), or a session × collection time interaction effect ($F(1,9) = 0.82$, $p = 0.39$). However, there was a main effect for collection time ($F(1,9) = 18.28$, $p = 0.002$). Bonferroni correction showed that state anxiety levels were higher after IAPS picture exposure (mean = 11.15, SE = 2.99) compared to before IAPS picture exposure (mean = 9.2, SE = 2.87), $p = 0.02$. Follow up *t* tests showed that anxiety levels were significantly higher following picture exposure only at the baseline testing session ($t(9) = -2.85$, $p = 0.02$).

4. Discussion

We aimed to test the effects of one night of sleep deprivation on emotion processing. To that end, we administered positive, negative, and neutral affective visual stimuli to sleep deprived individuals while simultaneously acquiring EEG ERP data and recording affective behavioral responses. In order to ensure that our LPP findings were not due to repeated testing effects, we also carried out a follow-up ERP experiment on a non-sleep deprived group. At both testing sessions in the sleep deprivation group salivary cortisol samples were collected and self-reported anxiety assessments were completed prior to and following the emotional picture task. To verify compliance to the protocol, sleep deprivation group participants were also asked to wear actiwatch sleep monitors and fill out sleep diaries.

Table 2
Means and standard deviations of cortisol and Self-Reported Anxiety Inventory (STAI) shown for before and after emotional picture viewing during baseline and sleep deprivation sessions.

	Baseline			Sleep deprivation	
	M	SD		*M*	SD
			Cortisol (μg/dL)		
Before pictures	0.313	0.17		0.382	0.21
After pictures	0.409	0.19		0.435	0.19
			STAI (state)		
Before pictures	9.8_a	11.67		8.6	8.22
After pictures	12.7_b	12.45		9.6	8.33

Note: Means within columns with differing subscripts are significantly different at $p < 0.05$ based on paired samples *t*-tests.

Our findings show that, as expected and consistent with previous findings, ERP responses to both emotionally positive and negative stimuli result in significantly larger LPP amplitudes compared to emotionally neutral stimuli. However, after sleep deprivation the LPP response no longer discriminated between the emotional (pleasant or unpleasant) pictures and the non-emotional pictures. Sleep deprivation did not differentially impair attention to the positive and negative pictures, rather, the lack of LPP modulation was driven by the increased LPP amplitude to the neutral pictures; after sleep deprivation the LPP to the neutral pictures was as large as the LPP evoked by emotionally laden stimuli. A possible interpretation of this finding is that sleep deprived people cannot switch off their emotions fast enough after having seen arousing stimuli. The idea that decreased attention resources after sleep deprivation decreases the ability to shift attention between emotional and non-emotional pictures is consistent with previous studies that have shown an impairment in the ability to shift attention between tasks following sleep deprivation (Couyoumdjian et al., 2010; Heuer, Kleinsorge, Klein, & Kohlisch, 2004; Jones & Harrison, 2001; Leenaars et al., 2012; McCoy et al., 2007).

The behavioral findings in the current study also support the idea that sleep loss results in impairment in attention switching. The behavioral rating task showed a trend for emotional pictures to be rated as less emotional following sleep deprivation, with negative (unpleasant) stimuli being rated as significantly less negative. Although the neutrally-generated LPP response reflected a difficulty in switching off the heightened emotion, the picture ratings better reflect a general decrease in attention resources. The fact that there is an apparent dissociation between the neutrally-generated LPP and the picture ratings reflects the mixed results seen in the literature. It is possible that neurophysiological emotion control processes become overwhelmed after sleep deprivation which results in behavioral changes that reflect this emotional instability (Chuah et al., 2010; Dahl & Lewin, 2002; Yoo et al., 2007). This reduction in emotional control processes could lead to either an under- or over-reaction to emotional stimuli possibly depending on the attention requirements of the emotional task at hand.

In addition, state anxiety scores significantly increased after picture presentation following a night of sleep, but showed no significant difference before and after picture presentation following a night of sleep deprivation. This agrees with previous work in rats which showed a decrease in anxiety following one night of sleep deprivation (Tartar et al., 2009). We were also interested in determining if sleep deprivation resulted in altered morning cortisol concentrations since an HPA stress reaction in itself could potentially explain changes in emotional processing. Cortisol levels did not change significantly either within or between testing sessions. This suggests that our observed affective changes were independent of glucocorticoid-mediated stress processes.

There are several limitations that should be considered in the present study. One potential limitation in the study was the small sample size. This is of concern because low sample sizes are thought to reduce the likelihood that the results represent a true effect (Button et al., 2013). Nevertheless, we are confident in the current findings. Not only were our major findings sufficiently robust as to yield statistical significance at the conventional levels, but the results are also in general agreement with a host of previous studies that have shown impairments in attention shifting following sleep deprivation (Couyoumdjian et al., 2010; Heuer et al., 2004; Jones & Harrison, 2001; Leenaars et al., 2012; McCoy et al., 2007). Another limitation to the current study is that, in spite of instructions to get a good night's rest, the average sleep duration the night before baseline testing was only 5 h and 9 min. This is in contrast with studies that have found the average sleep time of college students to be between 6 h and 20 min and 7 h (Lund, Reider, Whiting, & Prichard, 2010; Tsai & Li, 2004). It is possible that the situational demands of the study, requiring participants to present to the laboratory early in the morning for the baseline testing, may have contributed to the shortened sleep period. In reviewing the sleep diaries, participants generally reported later wake times for the three nights following baseline testing than for the day of baseline testing. Additionally, mean total sleep time for the same three-night period following baseline testing was 6 h and 29 min, which is more consistent with published average sleep times for college students. These data suggest that the shorter sleep duration may have been a direct result of an earlier wake time and a truncated sleep period. However, even with the short sleep duration the night before baseline testing, we still observed typical LPP amplitudes to the emotional and non-emotional pictures categories, suggesting that reduced sleep duration is sufficient to show typical LPP ERP responses to emotional and non-emotional picture categories. In addition, it is possible that drowsiness was related to the observed LPP effects after sleep deprivation since sleep deprivation can result in microsleeps and general attentional lapses (Lim & Dinges, 2008). However, it is not likely that these events were driving the modulation in the LPP after sleep deprivation observed here since the EOG site does not show a difference between the baseline session and the sleep deprivation recording session; there was no change in the picture rating response latencies, or a difference in the number of excluded ERP trials in the sleep deprivation compared to baseline testing day. One final consideration is that our manipulated variable of interest was the valence of the pictures. We did not analyze our findings by picture arousal (low vs. high). However, the arousal level of the pictures can also influence ERP paradigms involving attention processing (Rozenkrants, Olofsson, & Polich, 2008; Rozenkrants & Polich, 2008). Since many of our positive pictures were lower in arousal compared to the negative pictures, there could be an effect between pleasant and unpleasant conditions in terms of emotional arousal that was not investigated here. Thus, our observed effects should only be considered in terms of the applied stimulus selection criterion of valence (unpleasant, pleasant, and neutral pictures). However, since arousal was matched between picture sets for each valence category, the difference in neutral picture responses after sleep deprivation cannot be due to differences in arousal ratings between the picture sets.

In summary, we show that one night of sleep deprivation alters physiological (LPP ERP) and behavioral measures of emotion processing. Combined, these findings suggest that sleep deprivation results in an inability to shift attention between emotional and non-emotional stimuli which can result in divergent neurophysiological and behavioral responses. We are currently planning a series of follow-up experiments to explore how time of day, chronic sleep restriction, and sleep quality affect both physiological and behavioral measures of emotion processing.

Author contributions

RA, AF, and JT designed the study; RA and IC performed the experiments; RA, AF, and JT analyzed the data. RA and IC drafted the first version of the manuscript and AF and JT edited the manuscript. All authors discussed the results and interpretations.

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